Current Status of Advanced Radiation Resistant ODS Steel Development

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1. Introduction

A performance of in-core materials such as fuel cladding tubes is directly correlated with the safety of the nuclear reactor systems. Oxide dispersion strengthened (ODS) steel is one of the most promising structural material because of its superior creep and irradiation resistance on the basis of uniformly distributed nano-oxide particles with a high density which are extremely stable at high temperatures under a neutron irradiation environment [1-3]. Advanced radiation resistant ODS steel (ARROS) is being developed as a fuel cladding tube material for future nuclear reactor system applications. On the basis of out-of-pile creep properties of several designed samples, ARROS with a chemical composition of Fe-10Cr-1Mo-0.5Mn-0.1V-0.25Ti-0.35Y_2O_3 was selected as one of representative materials [1].

An optimized fabrication process for plates and tubes made of ARROS composition has been successfully established by means of a control of various process conditions in mechanical alloying, hot consolidation, hot/cold working, and heat treatment processes.

In this paper, the current status of ARROS development is introduced.

2. Experimental Procedure

2.1. Alloy design

ARROS has been designed on the basis of a martensitic phase with consideration of superior creep resistance, irradiation resistance, corrosion resistance, homogeneity, productivity, and reproducibility of ODS steel. For these characteristics, martensitic phase is more favorable than ferrite one because of the availability for the isotropy microstructure by a transformation with a high density of lath grain structures [4]. Many of the alloys for the nuclear reactor system application have 9~12 wt% of Cr with a minor portion of C. Mo is well known to be a good solid-solution element for high temperature strength in heat resistant alloys. Based on this design concept, ODS steels used in this study manly contained Fe(bal.)-10Cr-1Mo-0.1C in wt%. Some minor elements such as Mn, V, and Ti were added to get the phase stability and precipitate refinement [1].

2.2. Preparation of ODS steel samples

The ODS steel samples were fabricated by mechanical alloying and hot consolidation processes. Metallic raw powders and Y_2O_3 powder were mechanically alloyed by a high energy horizontal ball-mill apparatus, Simoloyer CM-20. Mechanical alloying atmospheres are thoroughly controlled in ultra-high purity argon gas. The mechanical alloying was performed for 40 hours with a ball-to-powder weight ratio of 10:1. High strength carbon steel balls were used as grinding media for the process. Milled powders were then sieved and charged in a stainless steel capsule. All powder handling processes for the weighing, collecting, sieving, and charging were conducted in completely controlled high purity argon atmosphere to prevent the oxygen contamination during the process. Sealed capsules were then degassed at 400^{o}C below 5×10^{-4} torr for 3 hours. The hot isostatic pressing was carried out at 1100^{o}C for 3 hours at a heating rate of 5^{o}C/min and following furnace cooling. Hot rolling at 1100^{o}C was done in a fixed rolling direction for a plate shape with 80% of a total reduction rate. Hot extrusion is also one of the consolidation methods. After the annealing in the furnace at 1100^{o}C for 2 hours, the capsules were extruded by 600 ton capacity of a press for several seconds with 6.3:1 of an extrusion ratio. Hot-extruded mother tubes were pilgered in combination with an intermediate heat treatment. A normalizing at 1150^{o}C for 1 hour and a tempering at 780^{o}C for 2 hours was followed.

The grain morphology was observed by FE-SEM. Thin foil specimens fabricated by an electro-jet polishing method were used to observe the precipitate distribution by a TEM. Creep tests were carried out at 700^{o}C.

3. Results and Discussion

3.1. Microstructure

Fig. 1 shows the microstructures showing the grain and anao-oxide morphologies of ARROS [1]. ARROS has a typical tempered martensite structure consisting of the very fine and equiaxed martensitic grains with finely dispersed carbides along the grain boundaries. The carbides are mainly identified as TiC and $M_{23}C_6$ which is a Fe, Cr-rich carbide induced by tempering heat treatment at 750°C. Fine nano-oxide particles were homogeneously distributed in the ARROS matrix. The average diameter and number density of the oxide particles were evaluated to be about 5.16 nm, 14 x 10^{21} m^{-3}, respectively.

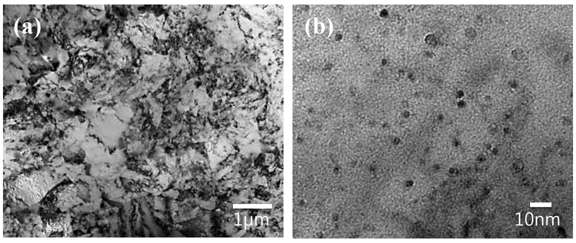

Fig. 1. Microstructures showing (a) grain and (b) nano-oxide morphologies of ARROS [1].

3.2. Creep properties

Creep rupture tests of ARROS are being performed in various stress ranges between 80 and 200 MPa at high temperatures. The creep test results at 700°C are plotted on the log-log scale in Fig. 2 [1]. The creep strength of ARROS was far superior in a comparison with the conventional steels such as HT-9, Type 316 stainless steel and MA957. This is due to the fine and homogenous microstructure features in ARROS as shown in Fig. 1, and lead to excellent creep rupture strength at high temperatures.

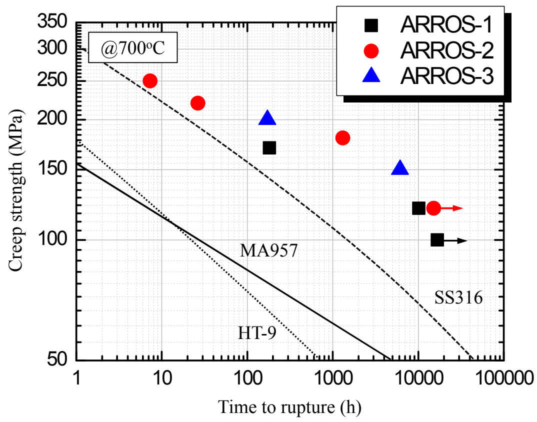

Fig. 2. Creep rupture strengths of ARROS and conventional steels [1].

3.3. Process development toward fuel cladding tube fabrication

After normalizing heat treatment, advanced radiation resistant ODS steel showed high hardness, about 800Hv. This is too hard to perform the cold working process for the tubing. However, furnace cooling heat treatment with a diffusional transformation at austenitic temperature makes the process quite easily. Outward appearances of mother tubes and pilgered tubes were shown in Fig. 3. This ODS steel rods were hot forged for the axis straightening and followed furnace cooling heat treatment. Through this process, the hardness could be lowered to 250 Hv and this is enough hardness level for tubing process. Pilgering process for the tubing was successfully set up and pilgered tubes were made.

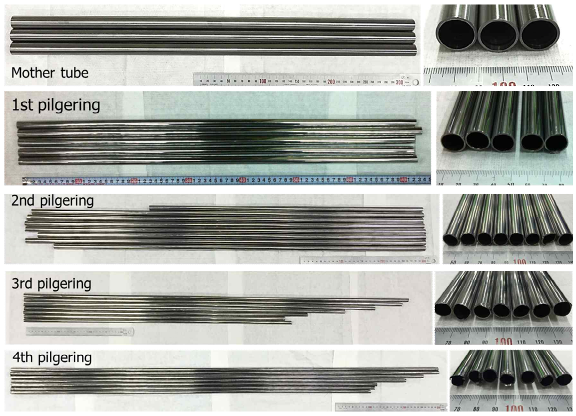

Fig. 3. ARROS tubes fabricated by pilgering process and intermediate heat treatment.

4. Conclusions

Advanced radiation resistant ODS steel (ARROS) with a chemical composition of the Fe-10Cr-1Mo-0.5Mn-0.1V-0.25Ti-0.35Y_2O_3 has been developed. On the basis of ARROS composition, the structural components such as plates and tubes were successfully fabricated. ARROS shows superior creep properties at high temperature.

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